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Effect of redundant shear strain on microstructure and texture evolution during accumulative roll-bonding in ultralow carbon IF steel

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Abstract

Accumulative roll-bonding (ARB) is a severe plastic deformation process that can effectively produce ultrafine grained (UFG) structures in metals and alloys. In previous investigations, the ARB process has often been carried out under high-friction conditions without any lubricant between materials and rolls, which may cause a large amount of redundant shear strain near the sheet surface. Owing to repetition of cutting, stacking and roll-bonding in the ARB, a complicated redundant shear strain distribution is expected through the sheet thickness. The purpose of the present study is to clarify the effect of the redundant shear strain on the microstructure and texture evolution during ARB. A Ti-added ultralow carbon interstitial free steel was deformed by up to seven cycles of ARB (a thickness reduction of 99.2%) at 500 °C, with or without lubrication, in order to investigate the effect of shear strain. Microstructural characterization by electron backscatter diffraction analysis was carried out at various thickness locations of the ARB processed sheets. The sheet processed by one cycle of ARB with good lubrication showed typical deformation microstructures uniformly throughout the thickness. In contrast, the specimen processed by one ARB cycle without lubrication had an inhomogeneous microstructure, and the fraction of deformation-induced high-angle boundaries increased close to the surface. Non-lubricated ARB caused through-thickness microstructural heterogeneity in low numbers of cycles, but repetition of ARB above five cycles finally produced quite uniform UFG structures. It was established that the microstructural parameters of the deformation structures can be basically understood in terms of the total equivalent strain, taking account of the redundant shear strain.

Keywords: Severe plastic deformation; Accumulative roll-bonding; Ultrafine grains; Interstitial free steel; Redundant shear strain

1. Introduction

Ultrafine grained (UFG) metals and alloys with the average grain size <1 μm are found to show outstanding mechanical properties, such as high strength, high toughness and superplasticity at low temperatures [1–6]. Applications of the UFG materials are therefore one important key issue in the near future. Severe plastic deformation (SPD) is the most effective method of producing UFG materials in bulk dimensions. Several different kinds of SPD process for bulk materials, such as equal-channel angular extrusion/pressing (ECAE/ECAP) [7,8], high-pressure torsion (HPT) [9] and accumulative roll-bonding (ARB) [10], have been developed so far. Among them, ARB is a promising process that has a potential for continuous production of large bulk sheet materials for industrial application.

In previous studies [11,12], the ARB process has succeeded in ultra grain refinement of various metallic materials. In almost all cases, repetition of the ARB process, typically above five cycles, can produce the pancake-shaped or elongated lamellar UFG structures. In parallel studies [13,14], it has also been suggested that the formation mechanism of the UFG during the ARB can be

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explained in terms of grain subdivision at a submicrometer scale [15–17] where initial coarse grains have been subdivided by deformation-induced high-angle grain boundaries. Though the submicrometer lamellar boundary structures are formed by conventional heavy cold rolling [16], it was pointed out by Huang et al. [18] that ARB can produce finer microstructures with a higher fraction of high-angle boundaries than conventional rolling, even after the same total reduction in thickness of the sheets. In fact, the ARB processed sheets are filled with the uniform UFG structures throughout the thickness, and the fraction of high-angle boundaries in the specimens is very high [19], so that they exhibit quite high strength. The reason for such effective formation of UFG microstructures with a large fraction of high-angle boundaries is a key issue to be understood.

Note that the rolling in the ARB process is not only a deformation process but also a bonding process (roll-bonding). In order to achieve good bonding, high rolling pressure in a high-friction rolling condition is effective, so that the ARB process has often been carried out under dry-surface conditions without using any lubricant. In that case, a large amount of redundant shear strain is introduced into the surface layers of the rolled sheet owing to the high friction between the sheet surface and the rolls ([20,21], see Appendix), which results in microstructure and texture heterogeneity throughout the thickness [22–26]. Owing to repetition of cutting, stacking and roll-bonding in the ARB process, more complicated redundant shear strain distribution throughout the thickness can be expected with increasing number of ARB cycles, which may cause more complicated distributions of microstructure and texture as well. It has been suggested that the redundant shear strain in the ARB may accelerate structure refinement [27,28], but the detailed effect of the redundant shear on the microstructural evolution has been unclear.

The purpose of this study is therefore to characterize quantitatively the through-thickness deformation microstructure and texture introduced by the ARB process both with and without lubrication, and to discuss the effect of the redundant shear strain on the microstructure and texture evolution during the process.

2. Experimental

2.1. ARB process

A Ti-added ultralow carbon interstitial free (IF) steel (Fe–0.002C–0.003N–0.01Si–0.17Mn–0.012P–0.01Cu–0.02Ni–0.072Ti mass%) was used in this study. The starting materials had a fully recrystallized single-phase ferrite structure with an average grain size of 20 μm, which was obtained by cold rolling and annealing. Sheets 1 mm thick, 30 mm wide and 300 mm long were prepared as starting materials for ARB.

A detailed procedure of the ARB process has been described previously [12]. After degreasing and wire-brushing, two sheets of the starting material were stacked to give a 2-mm-thick sample. The stacked sheets were held for 600 s at 500 °C in an electric furnace in an air atmosphere, and immediately roll-bonded by 50% thickness reduction in one pass. The roll-bonding was carried out at a roll speed of 17.5 m min^{-1} by a two-high rolling mill with the rolls 310 mm in diameter. Two different roll-surface conditions, a well-lubricated surface coated by mineral oil and a totally dry non-lubricated surface without any lubricant were used for the roll-bonding. These conditions were able to introduce a negligibly small amount and a large amount of shear deformation, respectively, as will be described in Section 3.1. In both cases, the roll-bonded sheet was immediately water-cooled after rolling. The rolled sheet was cut to half-length, trimmed and subjected to the next ARB cycle. This procedure was repeated up to seven cycles in both well-lubricated and non-lubricated ARB, without changing the rolling direction (RD).

2.2. Measurement of shear strain distribution

In order to evaluate the strain distribution through thickness of the ARB processed sheets, shear strain measurement was carried out by the embedded-pin method [29]. The method is schematically illustrated in Fig. 1. Before stacking two sheets of the starting material, a cylinder-shaped pin 2 mm in diameter and 1 mm thick, which was electrospark-machined from the same IF steel sheet, was embedded at the mid-width location of the upper sheet with the central axis parallel to the normal direction (ND).

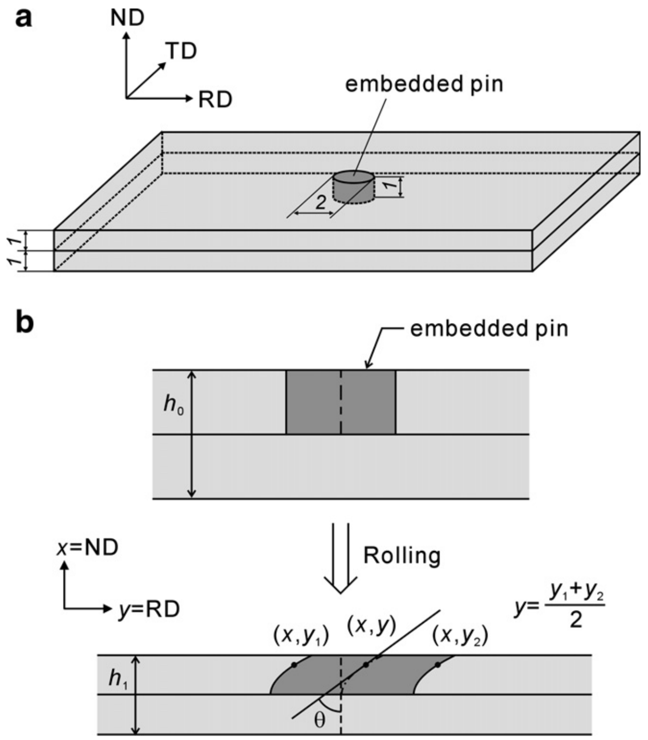

Fig. 1. Schematic illustration showing the shear strain measurement by embedded-pin method [29]: (a) overall sketch; (b) longitudinal section of the sheet.